REMARKS

STATUS OF THE CLAIMS

Claims 1-23 and 44-47 remain in the application. New claims 48-57 have been added.

The Office rejected claims 1-10, 12-22, and 44-47 under 35 U.S.C. § 102(e) as being anticipated by *Huber*.

The Office rejected claims 1-10 and 12-22 under 35 U.S.C. § 103(a) as being obvious over *Huber* in view of *Laakmann*.

The Office rejected claims 11 and 23 under 35 U.S.C. § 103(a) as being unpatentable over *Huber*.

SUMMARY OF THE INVENTION

The present invention is directed to a microfabricated Bragg waveguide comprising a continuous conformal coverage of multilayer dielectric cladding on the inner wall of a closed trench embedded in a substrate or a free-standing tube. The Bragg waveguide can be fabricated of semiconductor-compatible materials, such as silicon, silicon dioxide, and silicon nitride. The present invention is further directed to a Bragg waveguide wherein the layer thicknesses of the multilayer dielectric cladding can be selected to have a first cladding layer of slightly below the half-wave thickness to provide minimum radiation loss for linearly polarized light.

SUMMARY OF THE ART

Huber et al., U.S. Patent Application No. US2003/0035613 A1, discloses a hollow waveguide based optical switch. The method is disclosed for fabricating the waveguide in an open core, comprising depositing a reflective coating that can comprise a multilayer dielectric coating in the open core, filling the core with a sacrificial material, planarizing the sacrificial material, and depositing a separate reflective coating on the planarized sacrificial material.

Lackmann et al., U.S. 4,688,893, discloses a hollow waveguide having inner reflective layer comprising plural layers of dielectric. Preferably, the inner dielectric layers have quarter wave thickness.

ARGUMENTS

AMENDED CLAIMS 1–10, 12-22, AND 44-47 LIMITED TO A CLOSED TRENCH OR TUBE COMPRISING A CONTINUOUS MULTILAYER DIELECTRIC COATING DEPOSITED CONFORMABLY ON THE INNER WALL OF AN ANNULAR HOLLOW CORE, ARE NOT ANTICIPATED BY *HUBER* UNDER 35 U.S.C. § 102(e)

The Office rejected claims 1-10, 12-22, and 44-47 asserting that the Applicants' waveguide is anticipated by *Huber's* optical device. In particular, the Office asserted that *Huber's* multilayer dielectric cladding deposited continuously and conformably on the inner walls of the hollow core anticipates Applicants' claimed limitations.

Huber teaches a fabrication process that comprises deposition of a multilayer dielectric coating 1108 on the three inner walls of an open core 1102. *Huber's* trench is closed by a conductive layer 1114, typically a metal or a metal coated polysilicon layer, that is deposited on a planarized sacrificial material that fills the entire core. Because *Huber's* fabrication process requires that layers 1108 and 1114 be deposited in separate steps, Huber's reflective coating cannot be continuous around an annular core. *See Huber*, Paragraphs 42-43 and FIG. 7a-h. As Applicants have argued previously, *Huber's* waveguide will be lossy at the discontinuities between the separately fabricated reflective coatings, particularly for optical waves having electromagnetic field near the outside of the core.

Applicants have amended claim 1, and dependent claims 5, 6, and 10, and claim 12, and dependent claims 17, 18, and 22, to recite an "annular hollow core of arbitrary cross-section" to clarify that Applicants' closed trench comprises an annulus forming a complete ring about the hollow core. Support for this amendment is found in the Application at pages 12-17 and Figs. 3a-3d, 4a-4d, 5a-5h, and 6a-6b. In contrast to *Huber's* hollow core comprising three inner walls, Applicants' annular hollow core provides a continuous inner wall on which a continuous multilayer dielectric coating can be conformably deposited.

Furthermore, the Office argues that the continuity is broken at the "gas inlet". These gas inlets form an insignificant portion of the surface area of the inner wall of the annular hollow core. For example, a d = 10 μm diameter gas inlet spaced at l = 400 μm apart in a d = 10 μm diameter trench represents only d/4l < 1% of the inner wall surface area, enabling propagation of the optical wave

with low loss. *See* Application, page 13, line 27-30. Indeed, for short waveguides (*e.g.*, less than 1600 μm in length) the inner wall can be coated from the open ends of the waveguide and a gas inlet is not necessary.

With regards to claims 44-47, neither Huber nor the prior art teach or suggests a stack comprising a first cladding layer that is slightly below half-wave thickness that is optimized for minimum radiation loss for linearly polarized light. As discussed below for new claims 48-57, previous stacks comprise a first cladding layer that is quarter-wave thickness and are optimized to propagate TE modes.

Huber does not teach or suggest the limitation of a continuous multilayer dielectric coating deposited conformably on the inner wall of the annular hollow core of a Bragg waveguide. Accordingly, Applicants submit that this rejection is overcome and that amended claims 1 and 12 are in condition for allowance. Furthermore, Applicants submit that claims 2-10 and claims 13-22, which depend from and further define claims 1 and 12, respectively, are likewise in condition for allowance. *See* MPEP 2143.03.

<u>AMENDED CLAIMS 1–10, AND 12-22, LIMITED TO A CLOSED TRENCH OR TUBE COMPRISING A CONTINUOUS MULTILAYER DIELECTRIC COATING DEPOSITED CONFORMABLY ON THE INNER WALL OF AN ANNULAR HOLLOW CORE, ARE NOT OBVIOUS OVER *HUBER* IN VIEW OF *LACKMAN* UNDER 35 U.S.C. § 103(a)</u>

The Office rejected claims 1-10 and 12-22, asserting that the Applicants' waveguide is obvious over *Huber's* optical device in view of *Laakman's* teaching of a multilayer dielectric cladding. Applicants have argued, *supra*, that *Huber* does not teach or suggest the limitation of a uniform conformal multilayer dielectric coating on the inner wall of an annular hollow core. Nor does *Lackmann* teach or suggest such a limitation. Accordingly, Applicants submit that this rejection is overcome and that amended claims 1 and 12 are now in condition for allowance. Furthermore, Applicants submit that claims 2-10 and 13-22, which depend from and further define claims 1 and 12, respectively, are likewise in condition for allowance. *See* MPEP 2143.03.

<u>AMENDED CLAIMS 11 AND 23, ARE NOT UNPATENTABLE OVER *HUBER* UNDER 35 U.S.C. § 103(a)</u>

The Office rejected claims 11 and 23, asserting that the Applicants' waveguide having a core filled with a high refractive index material is obvious in view of *Huber's* optical device. Applicants have

amended claims 11 and 23 to recite an "annular hollow core." Applicants have argued, *supra*, that *Huber* does not teach or suggest the limitation of a uniform conformal multilayer dielectric coating on the inner wall of an annular hollow core and that amended claims 1 and 12 are in condition for allowance. Applicants submit that amended claims 11 and 23, which depend from and further define claims 1 and 12, respectively, are likewise in condition for allowance. *See* MPEP 2143.03.

NEW CLAIMS 48-57

Applicants have added new claims 48-57, to recite a Bragg waveguide comprising a multilayer dielectric cladding that is optimized to propagate linearly polarized light. Support for these new claims is found in the Application at page 9, lines 7, through page 10, line 18. Prior waveguides, comprising a quarter wave stack, have been optimized to propagate TE modes with low loss. *See* Yeh *et al.*, J. Opt. Soc. Am. 68(9), 1196 (1978); Fink *et al.*, Science 282, 1679 (1998); and U.S. Patent No. 4,688,893 to *Lackmann*. However, these TE-mode-optimized stack designs can be very lossy for the TM modes of linearly polarized light propagating in the waveguide. In contrast, Applicants' Bragg waveguide optimizes the stack design to propagate both modes with relatively low losses. In particular, Applicants' stack can comprise a first cladding layer slightly below the half-wave thickness. This is a novel and nonobvious result that is of great practical interest. Furthermore, this limitation was not taught or suggest by any prior art, in spite of the fact that quarter-wave stack designs have been know for 25 years. See enclosed article to be published by Hadley *et al.*, "Bragg fiber design for linear polarization," Optics Letters 29(8), 1 (2004).

REQUEST FOR CONTINUED EXAMINATION UNDER 37 C.F.R. §1.114

Applicant has submitted herewith a Request for Continued Examination. Please charge $770 for the RCE and any additional fees that may be required to Deposit Account No. 19-0131.

CONCLUSION

Applicants have amended the claims and urge that the application is now in condition for allowance.

Respectfully submitted,

Kevin W. Bieg

Kevin W. Bieg
Attorney for Applicants
Reg. No. 40,912
Ph: 505 284-4784
Sandia National Laboratories
P.O. Box 5800/MS 0161
Albuquerque, NM 87185-01

CERTIFICATION UNDER 37 CFR 1.8

I hereby certify that this correspondence and documents referred to herein were deposited with the United States Postal Service as first class mail addressed to: Commissioner for Patents, Alexandria, VA 22313-1450 on the date shown below.

Date: 4/12/04

By: Martha Trujillo

Bragg fiber design for linear polarization

G. Ronald Hadley, James G. Fleming, and Shawn-Yu Lin

Sandia National Laboratories, Albuquerque, New Mexico 87185-5800

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A new design is presented for Bragg fibers that allows low-loss propagation for linearly polarized light. Predictions based on a simple ray model show that approximately doubling the thickness of the first wall layer results in low losses at TM-like boundaries while keeping TE-like boundary losses manageable. This contrasts sharply with conventional quarter-wave designs that are extremely low loss for TE_{01} modes but very high loss for linear polarization. We fabricate Bragg fibers based on this design concept in a Si/SiO_2 system and verify experimentally that they propagate linearly polarized light with losses less than 6 dB/cm over a 60-nm spectral range. © 2004 Optical Society of America

OCIS codes: 220.2740, 230.1480, 230.7370, 060.2280.

The concept of a low-index-core fiber that confines light by incorporating Bragg reflector stacks into the walls was reported by Yeh and Yariv 25 yr ago.[1] The many practical uses of such fibers are well known and include (among others) dispersionless propagation of high-power pulses and detection of trace impurities in gases or liquids that can be made to flow through a hollow fiber. Numerous authors[1–5] have published theoretical treatments of the modal properties of such fibers as well. However, all of these analyses assume TE_{01} modes[6] wherein the electric field vector is always tangent to the fiber wall, resulting in quarter-wave stack designs.

Unfortunately, these treatments omit a case of great practical interest, namely, linear polarization. Linearly polarized modes are not only easier to generate but also allow peak powers on axis, a definite advantage for sensing applications. For this polarization a Bragg fiber made with quarter-wave reflectors will demonstrate loss[4] that is at least an order of magnitude higher relative to the TE_{01} mode due to a leakage through the stack in regions where the electric field is normal to the wall. Consequently, a different design is necessary for this case. In this Letter we derive equations for layer thicknesses for the two extreme (TE- and TM-type) boundary conditions (since the boundary condition for a circular fiber and linear polarization will vary smoothly between these extremes as a function of angle), resulting in a novel stack design. We also report the fabrication and testing of fibers based on this design in Si/SiO_2, demonstrating optical losses for linearly polarized light of less than 6 dB/cm over a 60-nm bandwidth centered on 1650 nm.

Design of the Bragg stack may be understood in terms of the simple ray model shown in Fig. 1. This model is valid for large-diameter fibers for which diffraction effects are minor and the fiber wall layers can be considered approximately planar. As plane waves strike an interface between two simple dielectrics, the ratio of reflected to incident electric field amplitudes is given by[7]

$$\frac{E_0''}{E_0} = -\frac{\sin(i-r)}{\sin(i+r)} \tag{1}$$

for TE polarization (electric field parallel to the interface) and

$$\frac{E_0''}{E_0} = -\frac{\tan(i-r)}{\tan(i+r)} \tag{2}$$

for TM polarization (magnetic field vector parallel to the interface). Using these equations and Snell's law, we can examine the phases of various light paths in Fig. 1(a) entering the first layer of refractive index n_1 from the core region (assumed to be air). Consistent with our assumption of large fiber diameter, the propagation constant for light in the core will be nearly along the axis, and it will refract into the first layer at the critical angle θ_c. For minimum loss we require that light traversing the two paths shown in the figure interfere destructively, leading to the relation

$$k_0 l = 2k_0 n_1 s + (2m + 1 + j)\pi, \tag{3}$$

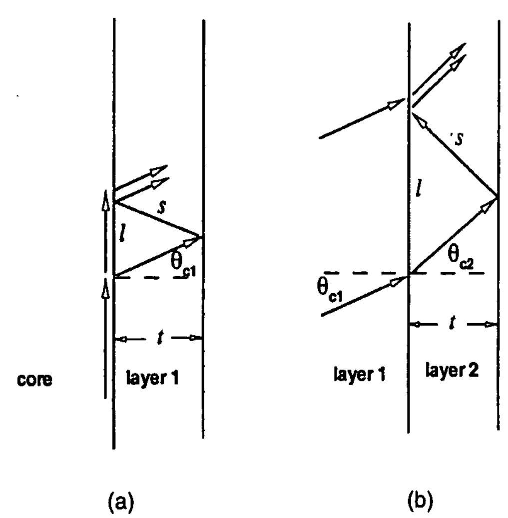

Fig. 1. Simple ray diagram used to derive optimum layer thicknesses for a large-diameter core surrounded by a multilayer reflecting stack: (a) Refractions and reflections for layer 1, (b) for all other layers.

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where j is 1(0) depending on whether there are an even(odd) number of sign flips caused by the two reflections, m is an integer, and k_0 is the propagation constant in vacuum. With $t = s \cos \theta_c$ and $l = 2s \sin \theta_c$ the above yields the following relation for the thickness of the first layer:

$$t_1 = \frac{(j + 2m + 1)\lambda_0 \cos \theta_c}{4(\sin \theta_c - n_1)}, \tag{4}$$

where λ_0 is the vacuum wavelength.

To analyze the remaining layers, we consider the different ray paths shown in Fig. 1(b). Again we want destructive interference and so require Eq. (4) to be satisfied, except that now l, n, and s correspond to layer 2 and m and j may be different from before. Inserting the same trigonometric relations used before, we again recover Eq. (4), except for the interchange of indexes and the easily shown fact that now θ_c is the critical angle for layer 2. Thus Eq. (4) may be used to predict all layer thicknesses provided that appropriate values of the parameters are inserted for each layer.

Now regarding correct values for j, we see that for TE polarization Eq. (1) shows that for Bragg stacks consisting of alternating high- and low-index layers the two reflections always produce either zero or two sign flips, leading to the choice of $j = 0$. For TM polarization the same is true so long as $i + r < \pi/2$. This condition is always fulfilled when each layer has an index of refraction $n > \sqrt{2}$, except for the first layer. For that layer, $r = \pi/2$ and no sign flip occurs at the core interface. Thus only one sign flip occurs, leading to the choice of $j = 1$. Using $\sin \theta_c = 1/n$ and values of m that produce the thinnest layers, we have the following relations for the optimum layer thicknesses:

$$t_1 = \begin{cases} \dfrac{\lambda_0}{4\sqrt{n_1^2 - 1}}, & \text{TE} \\ \dfrac{\lambda_0}{2\sqrt{n_1^2 - 1}}, & \text{TM} \end{cases}, \tag{5}$$

$$t_i = \frac{\lambda_0}{4\sqrt{n_i^2 - 1}}, \quad (i > 1). \tag{6}$$

For TE polarization, Eqs. (5) and (6) lead to thicknesses that are approximately quarter waves for $n \gg 1$, since the critical angle for such values approaches $\pi/2$. This result is in agreement with previous studies[4] and is appropriate for the TE_{01} mode, where the electric field is always tangent to the walls, and thus boundary conditions are TE-like. For TM polarization, however, the first layer thickness should be doubled according to Eq. (5), and since linearly polarized light will experience this boundary condition about half of the time, there is an apparent conflict over the best choice for the thickness of the first layer.

To resolve this conflict, we numerically calculate the propagation loss of the fundamental eigenmode of a one-dimensional slab waveguide made up of air surrounded by Bragg stacks of various designs composed of lossless materials. The results show that the TE-mode loss is indeed very low for quarter-wave stacks as expected, but the TM-mode loss for such designs is extremely high. In contrast, for a stack optimized for TM operation according to Eqs. (5) and (6), the losses for both TE and TM polarization are modest, showing this to be the preferred design. In practice, we decrease the first layer thickness by approximately 5% from the predicted values, which serves to substantially decrease TE losses without an appreciable increase in TM losses. The computed one-dimensional eigenmodes for a 10-μm-wide slab waveguide with four pairs of Si/SiO_2 reflecting layers on each side are shown in Fig. 2. As can be seen, the 3-dB TM losses are dominant but considerably reduced from the computed value of 36 dB/cm for a simple quarter-wave stack, thus confirming the predictions of the simple ray model described above.

We have successfully fabricated Bragg fibers following the above design in Si/SiO_2 on 6-in. (15.24-cm) silicon wafers using widely available silicon processing tools. The process steps can be classified generally as

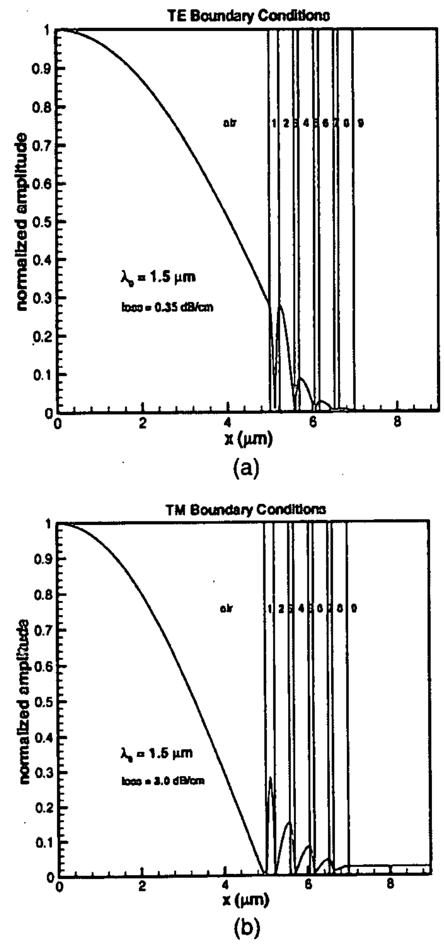

Fig. 2. Numerical computation of the fundamental mode amplitude profiles of a 10-μm-wide slab waveguide consisting of an air core enclosed by an Si/SiO_2 Bragg stack for (a) TE polarization and (b) TM polarization. Odd-numbered layers are Si ($n = 3.5$); even-numbered layers are SiO_2 ($n = 1.45$). Layer thicknesses are 0.219 μm for layer 1, 0.357 μm for SiO_2 layers, and 0.112 μm for other Si layers.

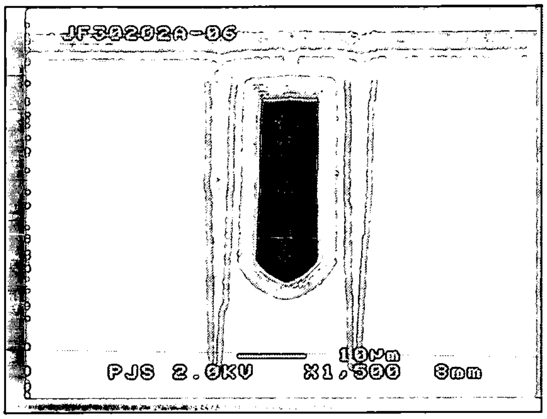

Fig. 3. Scanning electron micrograph of a fabricated Bragg fiber.

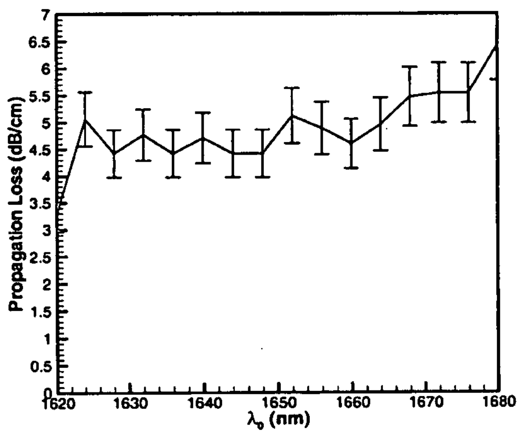

Fig. 4. Measured propagation loss versus wavelength for the Bragg fiber shown in Fig. 3.

the creation of an undercut trench, the sealing of the top of the trench, and the deposition of the mirror stack. The materials making up the mirror stack are introduced into the trench through widely spaced periodic openings along its length. The process relies on the low sticking constant (high step coverage) of chemical vapor deposition and diffusion processes, in particular the deposition of Si from silane, SiN from dichlorosilane and ammonia, and the thermal oxidation of silicon. Combinations of these processes allow the highly accurate creation of Si, SiN, and SiO_2 mirror layers. A scanning electron micrograph of the completed structure (employing only Si and SiO_2) is shown in Fig. 3.

We performed propagation loss measurements on the fabricated fibers by measuring the in-plane transmission of linearly polarized light (electric field vector vertical) through fibers of different lengths. Laser light from a wavelength-tunable source was laterally coupled into the input end of the fiber. The measurement was repeated for four fibers with lengths ranging from 300 to 2000 μm, and the loss of each wavelength was obtained by fitting the transmitted power to an exponential curve. The resulting loss is plotted versus wavelength in Fig. 4, demonstrating low-loss transmission over a 60-nm spectral range, limited by the tuning range of the input laser.

In summary, we have presented a novel device design for Bragg fibers, in which doubling the thickness of the first wall layer allows low-loss propagation of linearly polarized light. The design, although conceived with simple ray optics, has been confirmed with both one-dimensional and full-vectorial two-dimensional numerical models. We also fabricated Bragg fibers based on the thicknesses predicted by Eqs. (5) and (6) with readily available Si processing tools. We determined the propagation loss of these fibers for linearly polarized light to be less than 6 dB/cm over a 60-nm spectral range.

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. G. R. Hadley's e-mail address is grhadle@sandia.gov.

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